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SERT II GIMBAL SYSTEM

by Ralph J. Zavesky and Evert B. Hurst

Lewis Research Center

Cleveland, Ohio 44135

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16. Abstract

This report describes the gimbal system that was designed to mount the thruster and reposition the thrust vector of a mercury ion bombardment thruster through the center of gravity of the SERT II assembly. The SERT II assembly was launched February 3, 1970. The gimbal ring, gimbal mounts, bearings, actuators, and environmental testing are described. Due to the accurate alinements provided, it was not necessary to use the gimbal for the intended function. However, the gimbals were operated successfully numerous times in space after 8 months of storage.

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SUMMARY

The SERT II (Space Electric Rocket Test) spacecraft consisted mainly of two mercury ion bombardment thrusters mounted on gimbals. The primary purpose of the flight was to endurance test the ion thrusters. These thrusters are positioned on the spacecraft such that, when individually operated, one thruster will raise the orbit and the other will lower the orbit. If the thrust vector does not pass through the CG, the moments due to the offset thrust will cause the SERT II assembly to tumble. The uncertainty of thrust vector location is due to the unknown location of the thruster beam vector in flight and the inaccurate determination of the center of gravity of the SERT II assembly. It is possible that either or both of the variables could change during flight. To provide for these uncertainties during flight, the thrusters were mounted on gimbals.

This report describes the gimbal system that was designed to mount the thruster and reposition the thrust vector of a mercury ion bombardment thruster through the center of gravity of the SERT II assembly. The gimbal ring, gimbal mounts, bearings, actuators, and environmental testing are described. This includes the design concepts considered, the structural design, selection of materials, lubrication techniques, and how the dynamic and environmental testing problems were solved.

The gimbal systems passed all functional and environmental tests. The SERT II spacecraft was launched February 3, 1970. One thruster operated over 5 months and the other operated for 3 months. Because of the accurate alinement procedures used to mount the thrusters, it was not necessary to use the gimbals for in flight correction. After 8 months in space, the gimbal system was operated successfully numerous times.

INTRODUCTION

The SERT II (Space Electric Rocket Test) assembly consists of the second stage Agena, the spacecraft support unit, and the spacecraft. The primary purpose of the

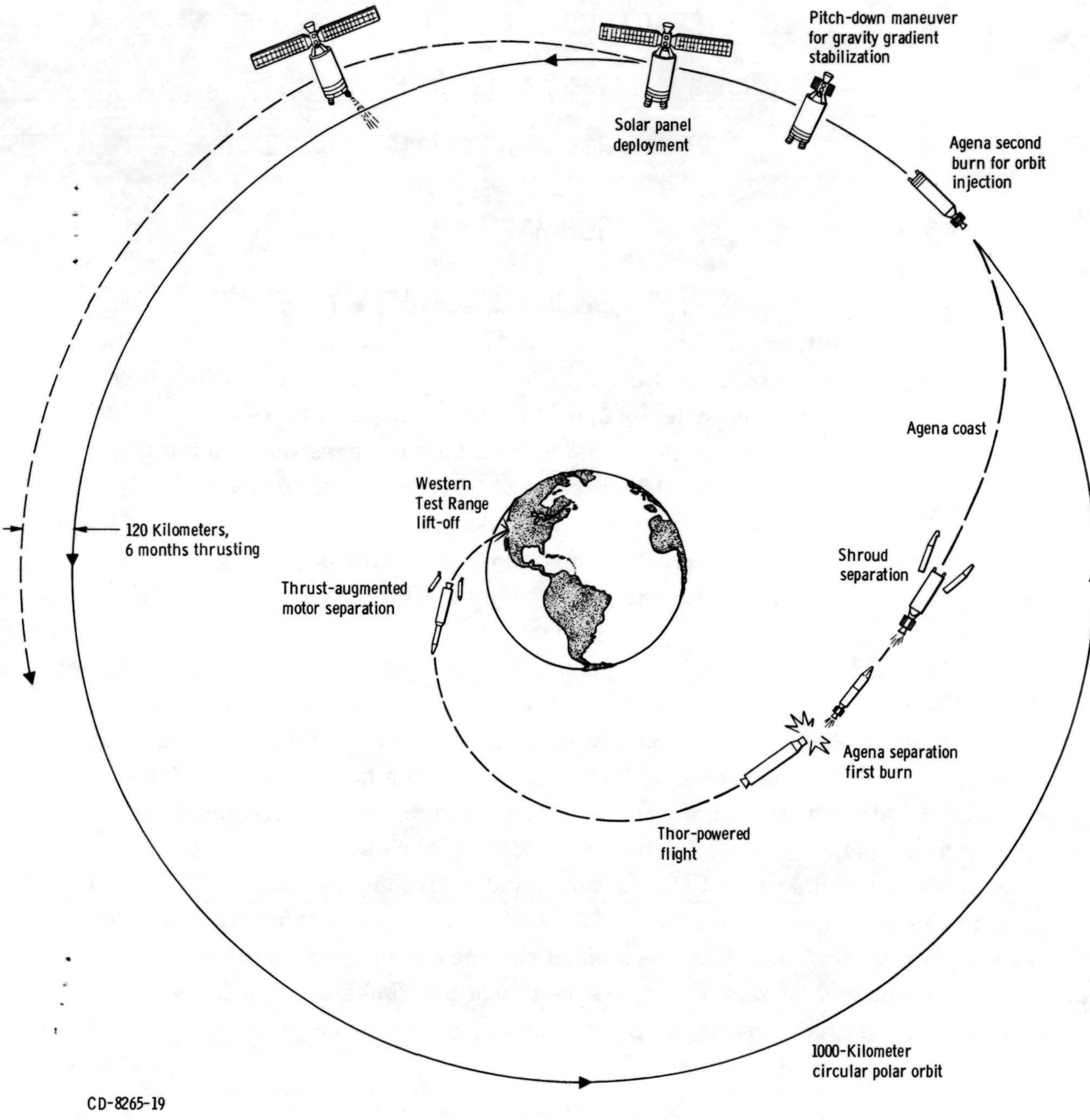


Figure 1. - Representation of SERT II flight sequence.

flight is to endurance test two mercury bombardment ion thruster systems. The secondary objectives are validation of ground test results; determination of ion thruster system operating characteristics in a space environment; development of operational procedures for ion thruster systems; and determination of reliability, endurance capability, and compatibility of an integrated thruster system.

The thrusters are positioned on the spacecraft so that, when individually operated, one thruster will raise the orbit and the other will lower the orbit (see fig. 1). It is desired that the thrusters be positioned on the spacecraft such that the thrust vector passes through the center of gravity of the SERT II assembly. If this thrust vector location is not obtained, the moments due to the offset thrust will cause the SERT II assembly to tumble. There are two factors which contribute to the uncertainty in prealining of the thruster beam through the center of gravity of the SERT II assembly. One is the uncertainty of the center of gravity of the spacecraft and the second is the uncertainty of the direction of the beam vector. It is possible that either or both of these variables could change during the flight. To provide for correction of these uncertainties during flight, the thrusters were mounted on the gimbal systems shown in figure 2.

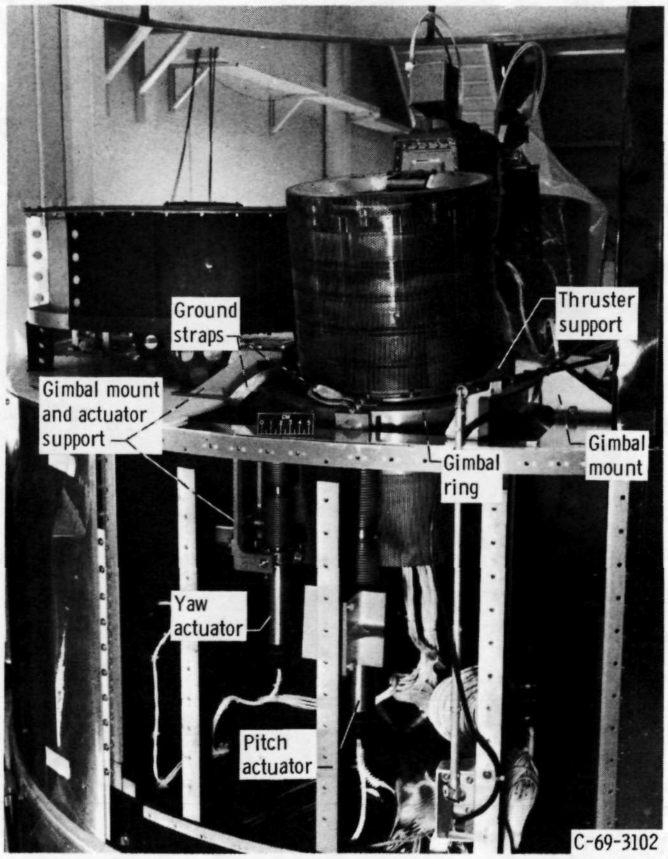


Figure 2. - Thruster gimbal system.

This report describes the design, fabrication, and testing of the SERT II thruster gimbal system. Several conceptual designs are discussed. The gimbal design is explained in some detail to show how the dynamic inputs due to environmental testing and launch loads were overcome. The actuator is described in enough detail to show the arrangement and the selection of materials for intermittent running in a hard vacuum for a period of 6 months. Appendixes A, B, and C discuss the three problems that were encountered during the testing phase of the program, namely, the flexural problem, the pin puller redesign, and the actuator motor evaluation.

GIMBAL SPECIFICATIONS

The design and development of the gimbal system was based on the requirements and constraints of the SERT II spacecraft. A series of functional and environmental specifications were developed to assure that the gimbal assembly and/or its components would perform its function.

Some of the important functional specifications are as follows:

(1) To provide a mechanism for alining the thrust vector through the center of gravity of SERT II in flight

(2) To provide location and adjustment for mounting the thruster assembly on the spacecraft through the calculated center of gravity of SERT II

(3) To serve as a mounting surface for a 25.9-kilogram thruster and a 2.72-kilogram ion beam probe

(4) To provide for gimbal travel in two coordinate axis of $\pm 10^{\circ}$ with a tolerance of $\pm 0.5^{\circ}$.

(5) To provide an actuation system that will

(a) Have nonjamming stops

(b) Be able to hold the thruster assembly in its final position after actuation.

(c) Have an end play at a stopped position that corresponds to less than 0.067 degrees

(d) Support a static load of 136.2 kilograms on each actuator in compression and tension

(e) Require power of less than 12 watts.

The components and/or assembly of the gimbal system were required to function properly after enduring a series of environmental tests. Component qualification specifications are listed in table I.

TABLE I. - COMPONENT QUALIFICATION SPECIFICATIONS

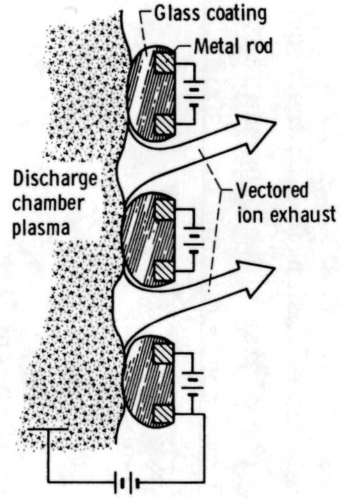
Type of test		Levels	Duration
Vibration (three axes)	Sine	1.27 cm double amplitude, 5 to 19 Hz	2 octaves/min
		9.0 g's (zero to peak), 19 to 2000 Hz	2 octaves/min
	Random	6.5 g's rms, 20 to 400 Hz	4.5 min/axis
		18.9 g's rms, 400 to 2000 Hz	4.5 min/axis
Shock		±30 g's	8 msec
Depressurization		Drop from 760 to 25 mm Hg	90 sec
Thermal vacuum pressure, 1.33×10^{-4} N/m^2	Low temperature	236 to 242 K	4 hr
	High temperature	342 to 347 K	2 hr
	Moderate temperature	333K	275 hr (continuously cycled at least five times from ambient to 333 K)

CONCEPTUAL DESIGNS

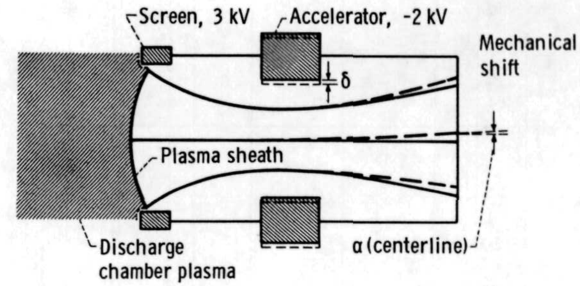
Several concepts were considered in the initial stages of design. Since the requirement for gimbaling the thrust in two coordinate axes came later in the program, there was not sufficient time to model all the concepts. It was desired to select a simple, reliable arrangement with the smallest number of parts and development problems. Some of the concepts are described in the next sections.

Electrostatic Beam Vectoring (Concept 1)

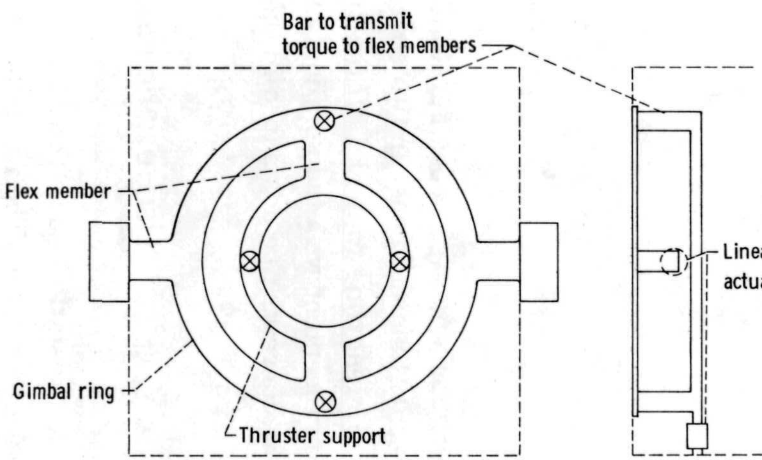
The electrostatic beam vectoring concept (see fig. 3(a)) does not require a mechanical gimbaling system. The ion beam is deflected electrically by embedding conductors in the accelerator plate in an arrangement that permits voltage biasing one side of the hole with respect to the other. This concept requires a large number of circuits and controls. This approach was dropped since background data were not available.



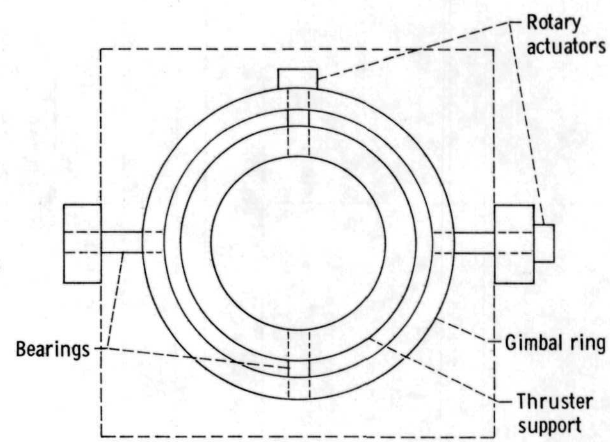
(a) Electrostatic beam vectoring.



(b) Mechanical shifting of thruster accelerator plate.

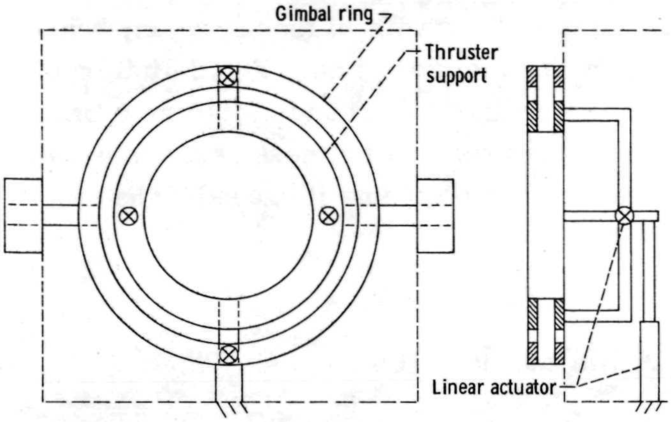


(c) Flex plate.

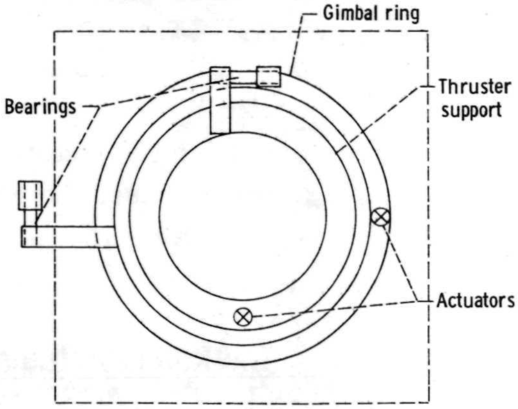


(d) Two rotary actuators and two bearings.

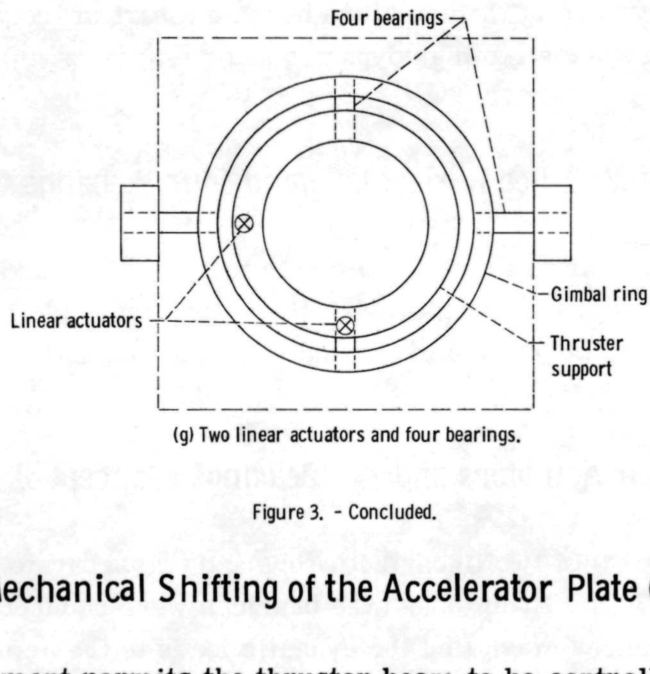
Figure 3. - Design concepts.



(e) Two linear actuators mounted horizontally and four bearings.



(f) Two linear actuators and two bearings.



(g) Two linear actuators and four bearings.

Figure 3. - Concluded.

Mechanical Shifting of the Accelerator Plate (Concept 2)

This arrangement permits the thruster beam to be controlled by misalining the accelerator plate with respect to the screen grid mechanically (see fig. 3(b)). This shifting of the ion holes causes a small opposite shift in the effective thrust centerline. This technique is limited due to the small amount of angular shift permitted before the accelerator plates are subject to rapid erosion.

Flex Plate (Concept 3)

The flex plate concept consisted of a thin plate with cutouts between the thruster mounting surface and the gimbal ring (see fig. 3(c)). The two axes of rotation were

obtained by the movement of two actuators mounted to yokes located 90^{o} apart. The flex members permitted deflection in torsion to take place without the use of any bearings. A model was built to demonstrate the principles of operation. The limitation of the static and dynamic loads in this case could not be maintained and at the same time permit rotation of $\pm 10^{o}$ in each axis. In addition the torsional stiffness necessary to carry the input loads increased the power required to a point that it exceeded the specified limit of 12 watts maximum.

Two Rotary Actuators and Two Bearings (Concept 4)

This arrangement consists of two rotary actuators and two separate bearings each located 90^{o} apart (see fig. 3(d)). The separate bearings are located directly in line with the actuators. This configuration permits using the actuator bearings as gimbal supports. This required that one of the actuators become a part of the gimbaling system and possibly would be subjected to high dynamic loads.

Two Linear Actuators Mounted Horizontally and Four Bearings (Concept 5)

This arrangement is similar to the flex plate with four bearings added (see fig. 3(e)). The position and arrangement of the actuators left the units vulnerable to high dynamic loads as well as increased the weight due to the addition of structural supports.

Two Linear Actuators and Two Bearings (Concept 6)

This arrangement consists of two linear actuators and two separate bearings each located 90^{o} apart (see fig. 3(f)). Even though the bearings were reduced to two, the offsets necessary for clearances magnified the dynamic loads to the actuators and the supports. In addition the gimbal system had the added weight of an extra actuator.

Two Linear Actuators and Four Bearings (Concept 7)

This configuration consists of two linear actuators and four bearings (see fig. 3(g)). The actuators were attached to the thruster support 90^{o} apart with their axis of movement in the same plane as the launch axis. The second actuator mounting permitted tying the gimbal ring to the thruster support. This arrangement gave the least amount

of cantilevered and offset parts, and thus reduced the dynamic input to the actuators and gimbal system. This was the concept chosen for the final design.

FINAL DESIGN

General Description

Concept 7 was selected as the optimum gimbal arrangement for repositioning the thruster vector through the center of gravity of the SERT II assembly if repositioning was needed. The arrangement provides for repositioning in a ± pitch and yaw axis or any combination within a $\pm 10^{\circ}$ cone angle. In addition the design serves as a base for mounting the thruster and feed system and as a means of attaching the thruster system to the spacecraft. The gimbal design is similar to that of a Hooke universal joint. It is composed of a thruster and feed system support, a gimbal ring, four bearings, two gimbal mounts, and two linear actuators. Two pin pullers and their brackets were later added to support the dynamic loads of the thruster system during launch.

The structural parts were machined from 6061 T-6 aluminum. The surfaces of the aluminum were iridited per MIL-C-5541A Type 1, Grade C, Class 3. This surface treatment was chosen in lieu of anodize to allow good electrical conduction and thus prevent electrical ground loop problems. Ground straps were attached from the thruster support to both the gimbal ring and the gimbal mounts.

The components were located such that the system is statically balanced about the pitch axis for launch loads. The concentrated mercury masses in the feed system were balanced in a yaw axis without disturbing the geometry of other spacecraft systems. The gimbal mounts were designed to carry the major thruster system loads into the spacecraft. The actuators and pin pullers were designed to carry the dynamic loads due to the system unbalance. The main components are described in the following sections.

Gimbal Structures

Thruster support. - The thruster support is the main structural member of the thruster system (see fig. 4). It serves as an interface between the thruster and the thruster propellant tanks. It consists of a single machined part containing two bearing supports for the gimbal ring, the mounting for the beam probe, and the two actuator attachments. The bearing supports consist of yokes that give double shear to the bearings. The beam probe mounting surface is integral with one bearing support. The attachment points of the actuators are located 90° apart and provide the capability of

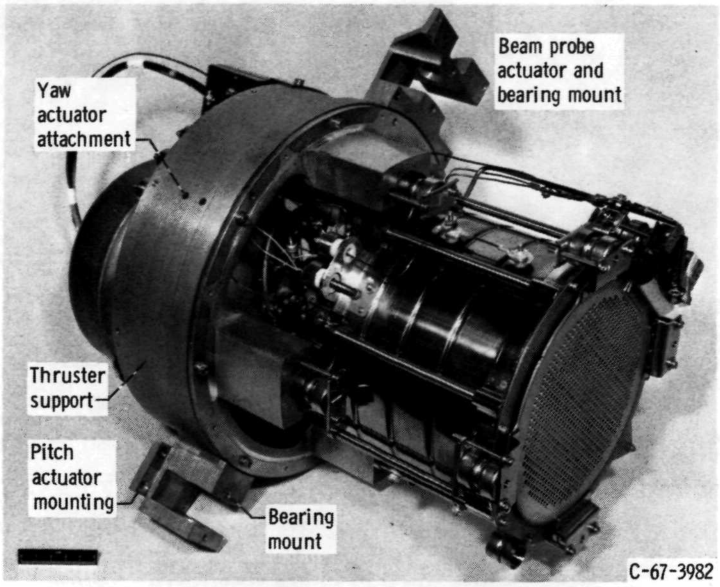


Figure 4. - Thruster support.

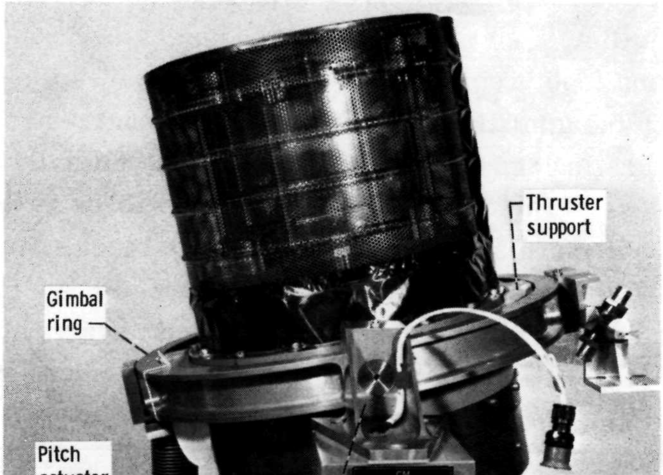


Figure 5. - SERT II thruster gimbal system.

tilting in the pitch and yaw axis. The pitch actuator attachment is integral with the second bearing mount. The side of the thruster support serves as the yaw actuator attachment.

Gimbal ring. - The gimbal ring (see fig. 5) serves as the bearing mounts and the structural tie from the thruster support to the gimbal mounts. It contains a rectangular cross section at four equally spaced bearing holes. The section between the holes is milled to form a 0.48-centimeter-thick channel section. On the basis of strength and stiffness to weight ratio alone, a hollow rectangular section would have been the best choice. However, the channel-shaped section was chosen to provide ease of machining, part quality, and a continuous bearing support. This size and shape of section is adequate for supporting both the torsional and bending loads.

Bearings. - In the design and selection of bearings it was desired to avoid the lubrication problems and the possibility of cold welding of mating parts in space. Sleeve bearings with dry plastic parts and flexural pivots were the two bearing systems considered. The flexures (see fig. 6) appeared to be ideal for vacuum application. These pivots are frictionless with no moving parts. Double ended flexural pivots of 2.54 centimeter diameter were originally selected that provided the anticipated radial load capacity and deflections desired. During the shock and vibration of the prototype spacecraft, these flexures failed. See appendix A for further explanation of the flexure failures. A three part sleeve bearing utilizing metal and plastic parts (see fig. 7) was designed to replace the pivots. The sleeve was designed to carry both radial and thrust loads without any metal to metal contact. The 2.54-centimeter-diameter sleeve part was made of delrin plastic and the shaft and stationary sleeve were made of 304 stainless steel. The delrin sleeve was captivated by final drilling in assembly. The stainless steel parts were secured by machining cylindrical tips on the end of screws. The plastic sleeve rotating relative to the stainless steel shaft met the dynamic input requirements and avoided the use of lubricants.

Gimbal mounts. - The two gimbal mounts provide a means of attaching the gimbal system to the spacecraft and also form a yoke for the two bearings and the gimbal ring (see figs. 5 and 8). The yoke arrangement provides double shear supports for the set of bearings. The mounts are single machined pieces with two ribs on the spacecraft side to carry the dynamic loads. One of the mounts contains an extension for supporting and indexing the pitch actuator relative to the thruster system.

Actuator

General description and requirements. - The actuators were the most critical portion of the design since these units were used to reposition, on command, the thruster system through the center of gravity of the SERT II assembly. In addition the actuators

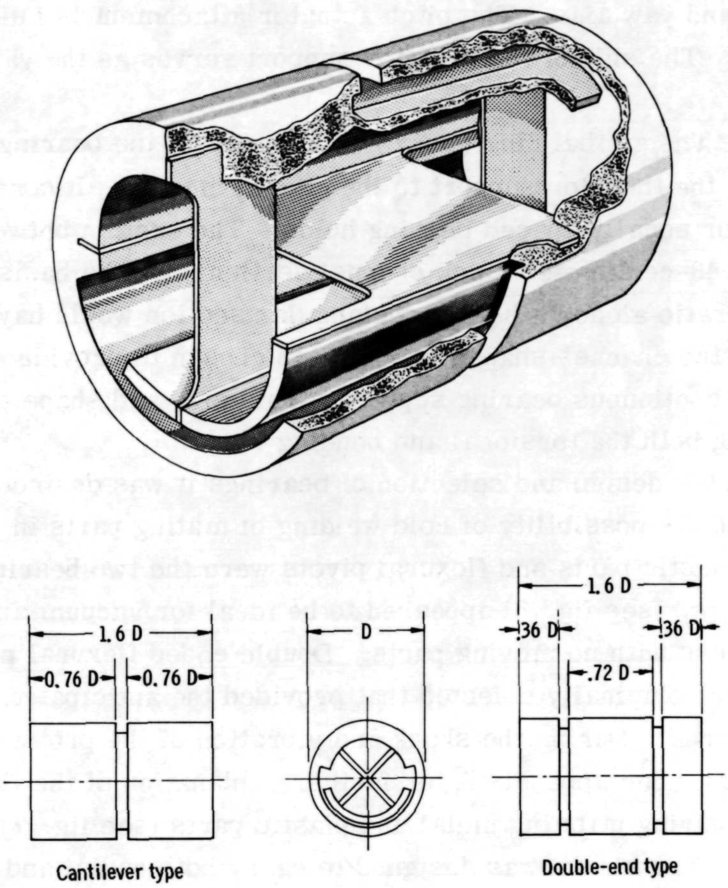


Figure 6. - Flexure pivots.

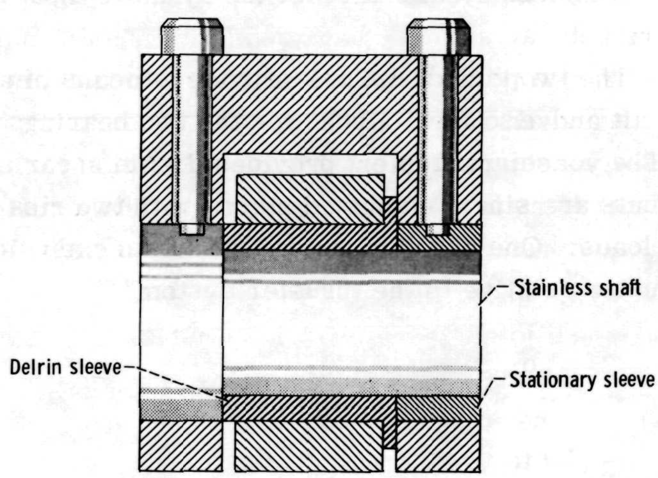


Figure 7. - Sleeve bearings.

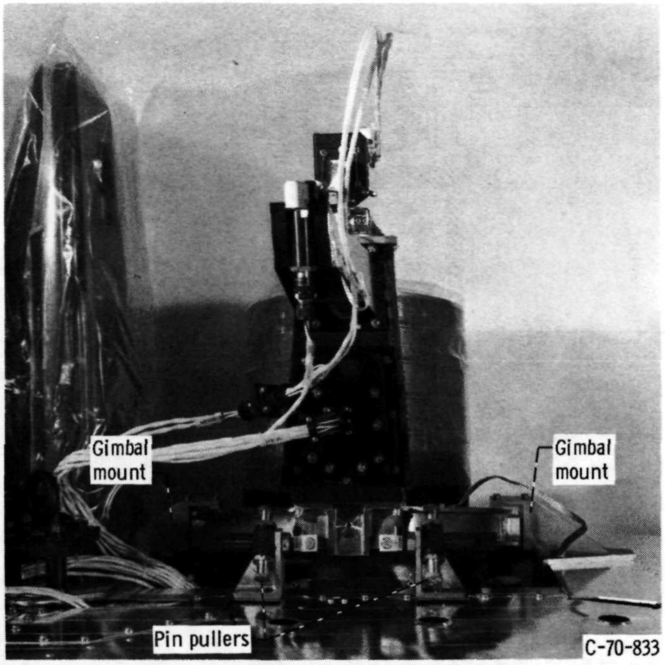


Figure 8. - Pin puller mounting configuration.

carried a portion of the dynamic loads due to unbalance in the thruster system.

It was attempted to provide maximum redundancy wherever possible to assure 6 months operation in space. First, wherever possible the materials of the various parts were chosen so that they would operate with no lubrication, in addition the bearings, gears, and all mating surfaces were lubricated with G-300 silicone grease. This lubricant provides adequate vapor pressure beyond 6 months provided the leak paths are controlled. Considerable design effort was expended to control the leak paths.

It was required that the actuator be capable of continued running without jamming or causing a power failure for a period of 1 hour. This is necessary in case a command to stop the actuator was not given during a pass of the spacecraft.

Linear actuators were selected to provide direct motion of the gimbal system and to act as load carrying members in the thrust direction. The actuators used the jack screw principle and gave a linear velocity of 3.40 centimeters per minute (see figs. 9 and 10). They were located 90° apart and mounted directly between the thruster support and spacecraft. Universal-type joints were provided at both ends of the actuators to give free and easy rotation of $\pm 10^{\circ}$ in pitch and yaw axis. The important components of the actuators are described in the following sections.

Motor. - It was desired to use a dc brushless motor because of elimination of arcing problems of brushes in vacuum and its low power requirements, but none were found to meet the environmental conditions. The motor selected was a 400-cycle 115-volt, hysteresis-synchronous motor. The basic motor velocity of 12 000 rpm was reduced to

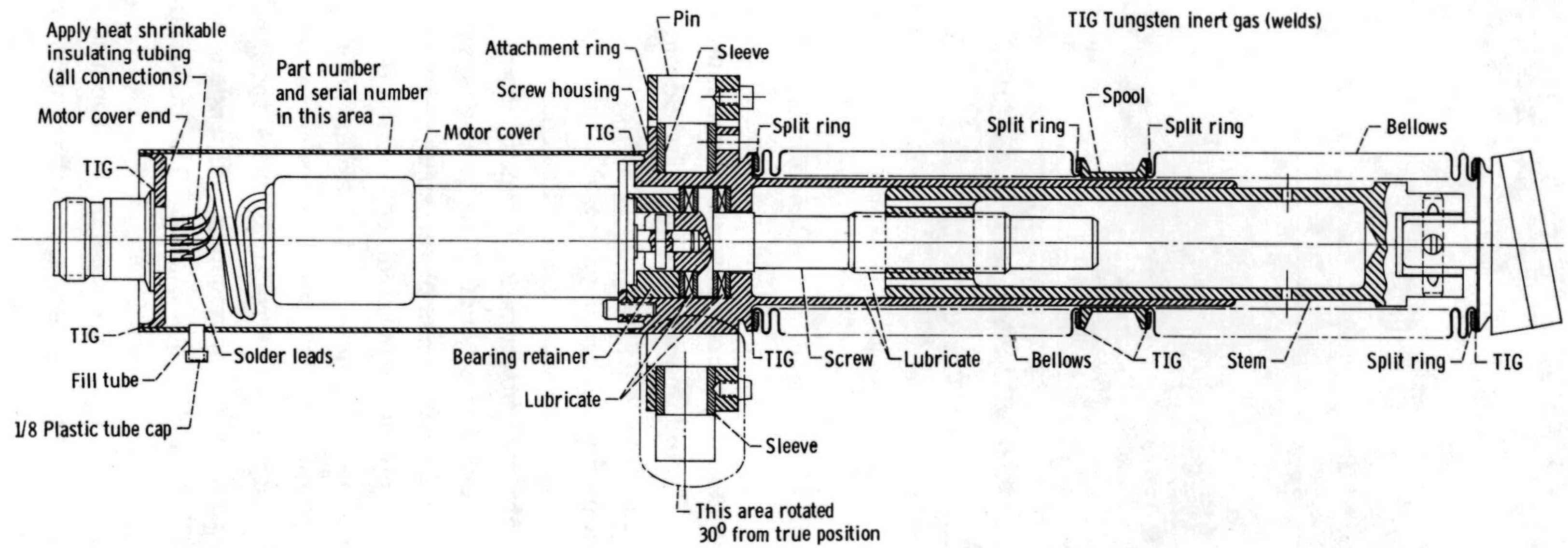


Figure 9. - Cross section of actuator.

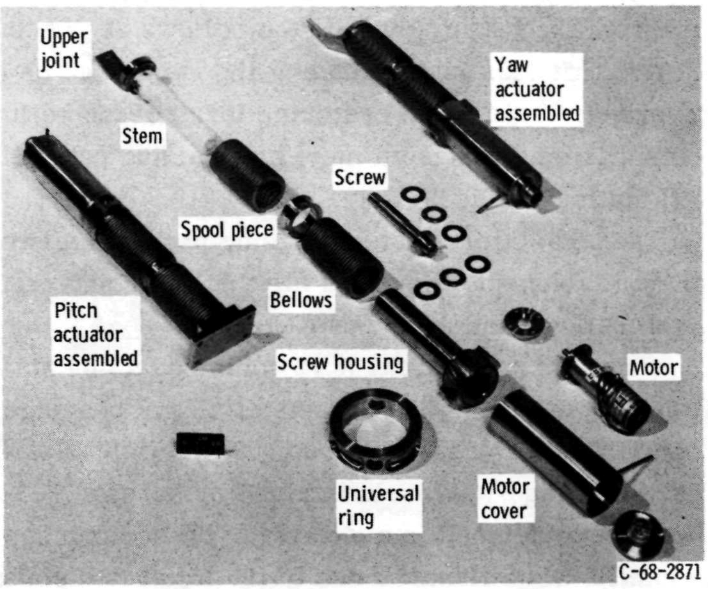


Figure 10. - Actuator parts (exploded photograph).

2.836 rpm with a planetary gear head. The nominal power required was 10 watts with a maximum of 12 watts at 125 volts and 239° K temperature. The bearing in the motor and the gears in the gear head were lubricated to fill about one third of the void space. The motor operates in either direction on command.

Screw. - The 304 stainless steel screw consists of a 1.27-centimeter 20 UNF thread with a plain shaft on each end with a diameter equal to the root of the thread. This permits the thread to run off and the motor to continue running in either direction. This satisfies the nonjamming requirement. Reversal of the motor causes rethreading within one revolution. The motor end of the screw is designed to carry the thrust bearing and to provide attachment to the motor.

Stem. - Delrin material was selected for the stem to avoid cold welding of mating materials and enhance its ability to operate in case the lubricants were lost. The stem provides 1.90 centimeters of mating thread for the screw. This gave a total actuator travel of 5.68 centimeters. The threads are chamfered on the ends to reduce the wear when the screw is not engaged and rotating (run off). The upper portion of the stem contains one half (yoke) of the upper universal joint.

Bellows and spool piece. - Two 316 stainless steel bellows and a 304 stainless steel spool piece cover the upper exposed portion of the actuator. The selection of two bellows and a spool piece was required due to the manufacturing limitation on the length of the bellows. The bellows act as a torsional restraint for the threads, a flexible cover over the moving parts, and as an energy-restoring device beyond a neutral position. The inner diameter of the 304 stainless spool piece was selected to provide a loose fit on the screw housing. This restricted the lateral motion of the bellows and also gave

adequate clearance for axial motion. When the actuator is completely extended so that the stem is unscrewed from the mating thread, the bellows are in tension. This leaves an axial force on the stem that aids in rethreading the stem back on the screw if the motor direction is reversed. This same restoring force of the bellows is available when the bellows are in compression. Tungsten inert gas welding per MIL-8611A was used to fasten bellows to all mating surfaces.

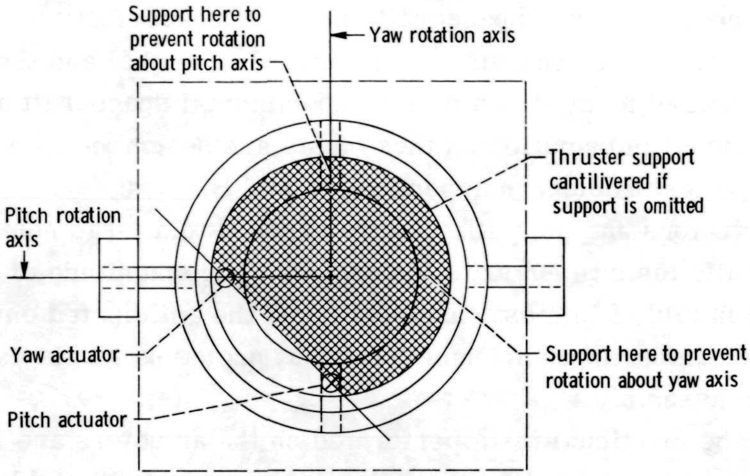
Screw housing. - The 304 stainless steel housing provided a cavity for the thrust bearings, motor, screw attachment, mounting for the lower universal bearings, and welding surfaces for the bellows and motor dust cover.

Universal joint. - The lower universal joint contained a 304 stainless steel ring and the lower portion of the screw housing. Two sets of sleeve bearings similar to the gimbal bearings were used. The bearings contained a 304 stainless steel pin and an outer sleeve of delrin. These bearings were held in place by screws. The final location and drilling for the screws was performed in assembly. These bearings had replaced 1.27-centimeter-diameter cantilevered flexures due to the failures discussed in appendix A. The upper universal joint consisted of a clevis type of arrangement with the stem providing a U-shaped part (yoke) and the attaching bracket a similar U-shaped part. A phosphorous bronze gimbal block was inserted between these two yokes to form the universal joint. A long and two short 17-4 PH stainless pins were used as pivots. These pins were captivated by notching the long pin in the center and securing the short pin on each side by a 0.076-centimeter-diameter stainless steel wire.

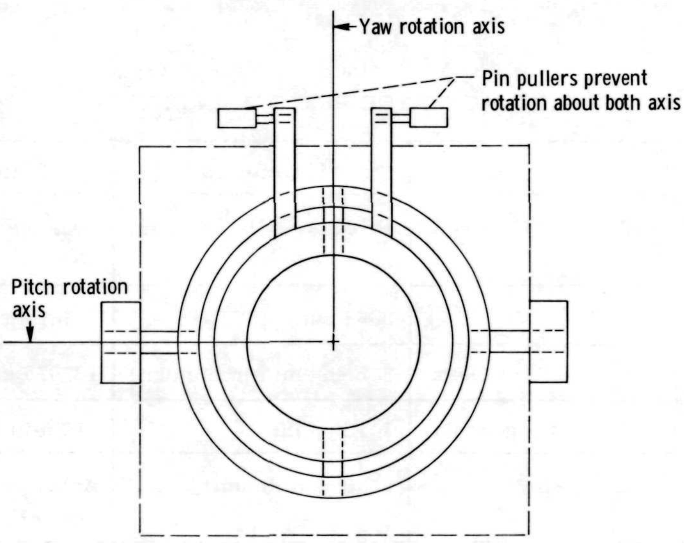
Motor cover. - The 304 stainless steel cover provided a method of lubricant vapor control for the motor section of the actuator. It also provided means for mounting the electrical connector and for protection of wiring and the motor against accidental mechanical damage.

Pin Pullers

It was determined by a series of experimental vibration tests that mechanical restraints were necessary to support the dynamic unbalance of the thruster system because the amplitudes of the experimental units at resonance were higher than the design load factors of the thruster system. This mechanical restraint was met by use of two pyrotechnic pin pullers (see figs. 8 and 11) mounted on the spacecraft and consisting of 0.64-centimeter-diameter pin and piston with single bridge dual squibs for withdrawing the pin from the thruster support. A problem with a shear wire which retains the pin prior to firing was encountered. The solution of this problem and the redesign of the pin pullers are further discussed in appendix B and in reference 1.



(a) Ideal support system.



(b) Final support system.

Figure 11. - Positions of support required for gimbals.

Testing

General description. - The description of the testing will be confined mostly to component prototype testing since these magnitudes are more severe than either the flight component acceptance, prototype spacecraft, or flight spacecraft tests. The gimbal structure was not tested as a separate component. The gimbal and thruster assembly was vibrated and shocked many times on the experimental spacecraft at prototype spacecraft levels. Additional information on these tests are described as a part of the flexural pivot and pin puller problem in appendixes A and B.

The gimbal actuators and pin pullers were exposed to a large number of performance environmental and life tests to evaluate the design. The magnitude of the prototype component tests listed in table I in most cases exceeded the anticipated environment by a factor of 1.5. The number of components tested at prototype levels usually consisted of a set to make an assembly.

Actuators. - The functional tests performed on the actuators are listed in table II. These checks were performed before and after each test listed in table I. The actuators passed all the functional and environmental tests.

TABLE II. - ACTUATOR PERFORMANCE TEST

Tests		Magnitudes	Criteria and remarks
Leakage filled with helium at 4861 N/m^2		Pressure, 10^{-6} mm Hg or lower	Leakage rate, 10^{-6} cc/sec or less
Stroke		5.38 cm	Tolerance, ±0.15 cm
Travel rate	Linear	3.6 cm/min (minimum)	±0.025 cm/min
	Angular	$1^{\circ}10'$/min	±10 min/min
Gimbal travel from center position		$9^{\circ}30'$ (minimum)	Actuator run off at both ends in assembly
Static load		136.2 kg	Actuator run off at both ends in assembly - no permanent distortion
Coast - when power is removed		Not to exceed 0.025 cm	Tested in gimbal assembly
End play		0.067°	Maximum
Voltage		105 to 125	Power not to exceed 12 watts maximum
Power factor		0.9	Minimum with capacitor box

Life tests were performed on the actuators in the gimbal assembly after prototype environmental component tests. The actuators were cycled continuously for ten complete strokes at 1 atmosphere. This was required to demonstrate that the delrin plastic thread would perform satisfactorily. Since the gimbal system was intended to make only small corrections the completion of ten full stroke cycles without failure gave a large safety factor. The nonjamming or dissengaged life of the end of the plastic threads was evaluated with the actuators both fully extended and contracted. Under this condition, the actuators were operated for 1.5 hours. This operation causes the stainless steel thread to ride over the end of the delrin thread every revolution. The thread engaged properly after the motor direction was reversed. This operation time limit was chosen to represent the period of one orbit. In case a command was forgotten the actuators would still be capable of operating.

The actuators performed all tests satisfactorily except for a motor failure encountered during final ground testing of the spacecraft. The failed actuator was inspected carefully and a series of tests was performed on the motor in an effort to determine the cause of failure. This is further described in appendix C.

Pin pullers. - Three pin pullers were subjected to a series of performance tests before and after the environmental tests listed in table I. The thermal vacuum testing was modified slightly. The high temperature test was omitted. The low temperature test was conducted at 233° K instead of 239° K (average) and the time was extended to 25 hours instead of the normal 4 hours. The moderate temperature was dropped from 333° to 311° K and the time was reduced from 275 to 24 hours. At the end of the thermal vacuum testing, the three pin pullers were fired. Two were fired after the low temperature and one after the moderate temperature test. These performance tests are listed in table III. Before launch a total of 11 pin pullers and 22 squibs had been fired without a failure.

TABLE III. - PIN PULLER PERFORMANCE TESTS

Test	Magnitudes	Criteria or remarks
Bridge wire	1.1±0.01 ohms	Resistance between pin A and B
Cartridge	Torque, 11.5±2.3 cm kg	No movement counter clockwise
End plug locking test	Torque, 11.5±2.3 cm kg	No visible movement counter clockwise
Dielectric test	500 V dc applied dielectric resistance 100 megohms minimum	Resistance from shorted pins to case of squib
No fire test after thermovacuum	3.8 V dc and 1 amp for 5 min	No fire
All fire after thermovacuum	22 V dc and 5 amp	Fire and catch piston - no visible leakage of byproducts

CONCLUDING REMARKS

This report discusses the design and testing of the gimbal and actuator system on which the electric thruster of the SERT II spacecraft was mounted. The requirements of the gimbal system were twofold: (1) to provide adequate structural mount for the thruster to the spacecraft during launch and flight environment, and (2) to provide a means of changing the direction of the thruster beam vector during flight. The system consisted of a gimbal ring, four bearings, and two linear jack-screw-type actuators.

The gimbal and thruster systems passed all environmental testing. The SERT II spacecraft was launched on February 1, 1970. Both thrusters were operated, one for over 5 months and the other for 3 months. Because of the accurate alining procedure used to mount the thruster system so that the expected beam vector would pass through the calculated spacecraft center of gravity, the gimbal system did not have to be used for in-flight correction.

However, the gimbal system was used during the flight for a task that was not anticipated. The thruster failures were believed to be an eroding of the accelerator grid due to ion bombardment which caused a molybdenum whisker to grow between the accelerator grid and the screen grid. This caused a short in the high voltage system of the thruster and power conditioner. An attempt was made to shake the whisker loose by running the gimbal actuators off the end of the threaded shaft for some length of time. When the threads reached the end, the system would drop back one pitch of the thread causing a small shock or bump. Although this shock was not enough to dislodge the whisker, monitoring the current to the motors indicated that all four gimbal actuators ran even though they had been inoperative for approximately 8 months in space. Thus the gimbal system designed for SERT II was successful both during ground testing and flight of the SERT II spacecraft.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 30, 1971,
164-21.

APPENDIX A

FLEXURAL PROBLEM

Bendix flexural pivots were originally selected as bearings in the gimbal system. The 1.27-centimeter cantilevered flexures supported the lower joint of the actuators and the 2.54-centimeter double end flexures supported the gimbal ring. These flexures consist of hollow cylindrical sections joined on the inside by thin hardened plates positioned so that their planes are normal to each other and the intersection of their planes is on the desired axis of rotation (see fig. 6). The selection of flexures gave several advantages over the sleeve bearing. The problem of sliding and possible cold welding in space was eliminated. Lubrication was not required and this removed the possibility of outgassing and contamination. The flexures can operate in vacuum and at wide ranges of temperature. The flexures stored energy when the gimbal system was displaced from the normal position. This energy was available for aiding in the return of the actuators to the neutral position. The flexures were designed to carry mostly radial loads. Even though the loading capacity in all planes was not ascertained it was thought that the specified radial load capacity was large enough to support loads in all planes.

The flexural pivots passed the earlier experimental tests with dummy pin pullers. During additional experimental vibration and shock testing, the dummy pin pullers failed and some of the actuator flexures failed. It was assumed that the dummy pin puller failure had permitted higher loads to reach the actuators and thus caused the flexure failure. During the vibration and shock of the prototype spacecraft, the pin pullers failed and further inspection indicated that some of the gimbal ring and actuator flexures failed. The thin hardened plates fractured or bent at or near the fastening of the plates to the inner semicircular plate. At this point it was decided to revibrate the flexures with an experimental gimbal system, with flight-type pin pullers, and with the experimental spacecraft as a fixture. The flexures were inspected after each axis of prototype vibration and shocks. One gimbal ring flexure failed during a 13 g shock loading input to the experimental spacecraft in a lateral direction (90° from the manufacture's published maximum load). The exact magnitude of the lateral loads at the flexures were not known. The flexure never failed in vibration or shock in the thrust direction of the spacecraft but were marginal on the basis of the lateral test specifications. A study of the vibration and shock data indicated very little increase in amplitude after failure of the flexures. The gimbal system was still operational. Since the gimbal flexures were already the largest available and there was a possibility of a loose flexure floating free after failure to possibly jam or short circuit the high voltage thruster, the use of flex-

ures as bearings was abandoned. A sleeve bearing system as described earlier (see fig. 7) was designed to replace the flexures.

APPENDIX B

PIN PULLERS PROBLEM

The pin pullers as purchased from Holex Corporation (see fig. 12) failed during the prototype spacecraft vibration test. The 0.032 diameter aluminum shear wire which retains the piston and pin assembly prior to firing failed due to a combination of forces

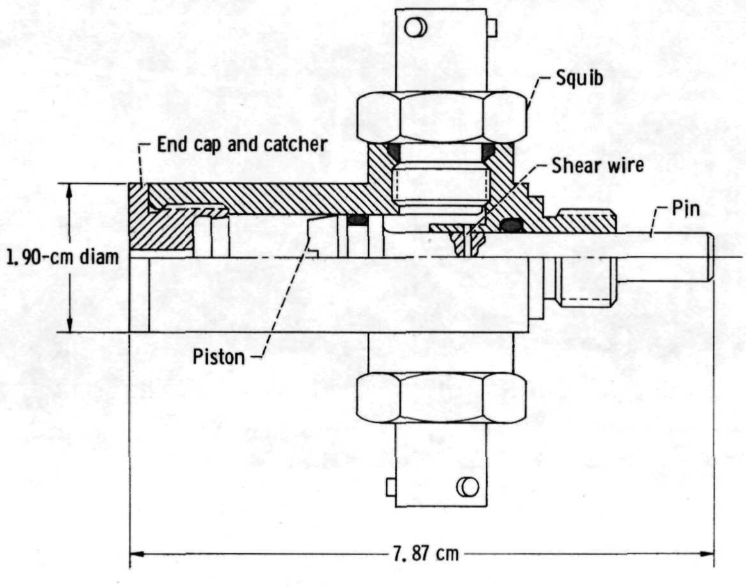


Figure 12. - Cross section of purchased pin puller.

acting on the pin and piston of the pin puller. The mating 17-4 PH stainless steel pin that fits inside the aluminum thruster support did gall. This galling process permitted the coefficient of friction to increase enough to permit the transfer of larger torsional, axial, and/or bending loads along the pin and piston to the shear pin. A program was initiated to determine the basic failure mode and to collect information for redesigning the pin pullers. The failure mode is discussed further in reference 1. By the use of high-speed motion pictures during vibration testing, it was discovered that the combination of torsion and axial loading was the major causes of failure. It was also discovered that the testing sequence governed the mode. If vibrated in the z and y axes first and then in the thrust axes no failure would occur. On the other hand, if vibrated in the thrust axis first and then the y and z axes, a failure would occur in the z axis as a result of galling in the first two axes. The frictional loading was reduced and the galling

was eliminated by inserting a nylon bushing between pin and the thruster support (see fig. 13). The shear wire was relocated behind the piston and pin assembly (see fig. 14). This relocation and the addition of a secondary piston eliminated the torsional and possible bending modes.

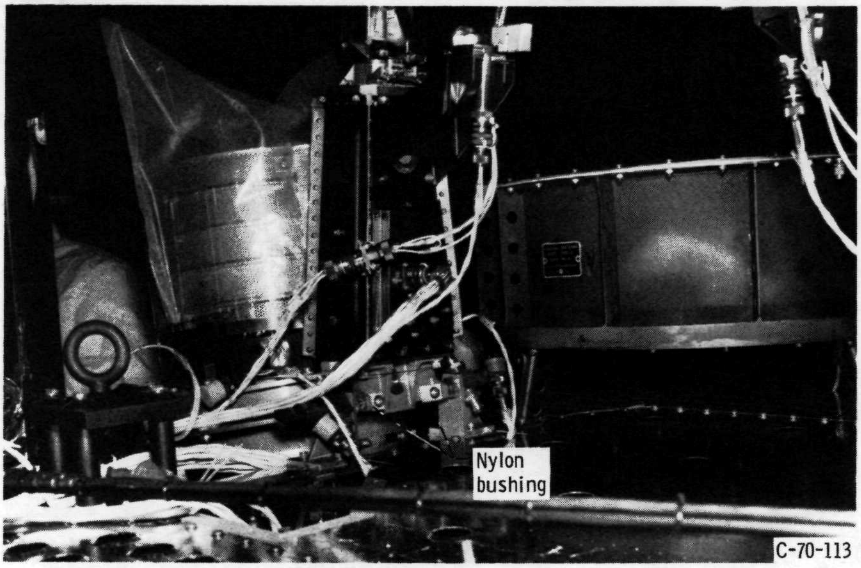


Figure 13. - Delrin pin puller nongalling sleeve.

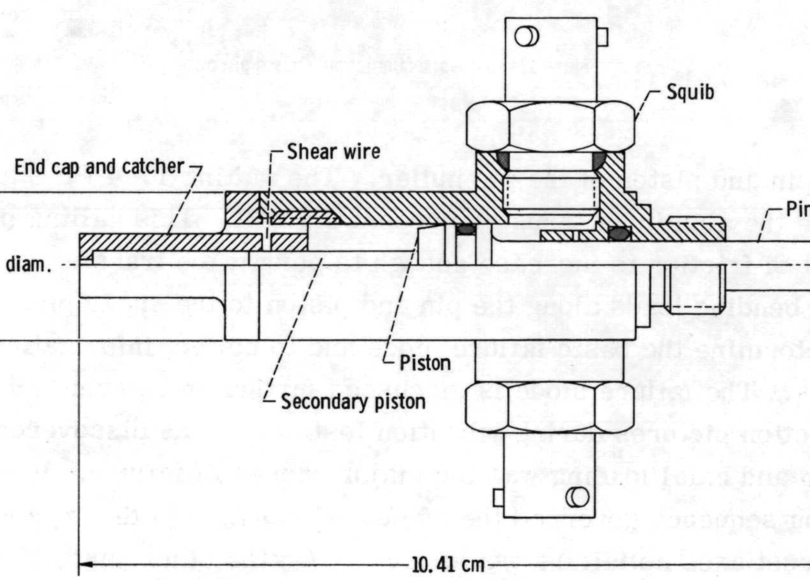


Figure 14. - Cross section of modified pin puller.

APPENDIX C

ACTUATOR MOTOR EVALUATION

A gimbal actuator failed to operate long enough to permit realining of the thruster system on the flight spacecraft. This occurred at ambient conditions just before shipment to the launch site. It was urgent that the cause of failure be determined. In addition it was necessary to know if the other actuators had been damaged in the alining process and what was the recommended operation cycle in orbit.

The actuator was carefully disassembled and inspected in stages to determine the failure. Resistance readings indicated that the common (black lead) winding wire was open. The solder terminals were examined by a 40 power microscope. A ball of varnish was located next to the common terminal. It looked like a poor solder joint. By applying a small amount of pressure on the terminal it was possible to get continuity through the common windings. The solder was carefully sucked from the terminal exposing the open lead. By the use of a microscope it was evident that only the extreme tip of the motor winding wire was soldered. Sufficient varnish had not been removed from the end of the winding wire. Thus, the cause of failure was a poor solder junction from the motor winding to the terminal strip. It was concluded that in the operation of the actuator the motor winding temperature had increased enough to cause separation in the solder joint.

All flight backup actuators had already completed a total of three full strokes in both directions during the performance test at 1 atmosphere. The continuous running had been limited to one full stroke before and after vibration and shock and thermovacuum testing. In addition each actuator had operated intermittently during a 48-hour vacuum test at 322° K.

It was decided to run two motor tests and two actuator tests in an effort to determine if the flight actuators had been operated too long and to establish a duty cycle in orbit. These tests are described in the following sections.

Motor winding calibration (fig. 15). - A motor was soaked at various temperatures until stabilized and then the resistance of the windings was measured. This curve was used to determine the temperature of the windings from the resistance against time tests to follow.

Winding resistance as a function of time at 347 K (165° F) and 1 atmosphere (fig. 16). - The manufacture suggests that the environment in which the motor operates be limited to a maximum temperature of 358° K. The motor was tested at 347° K to allow a small safety factor. The same motor as used in the first test was operated for 115 minutes. The motor windings reached a temperature of 442° K. This could be the recommended upper temperature of the windings.

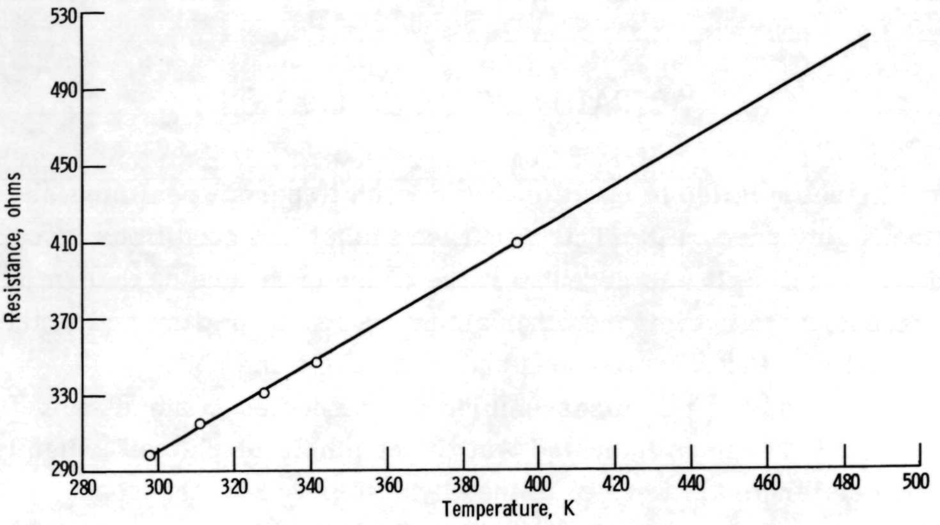


Figure 15. - Resistance of windings plotted against motor temperature.

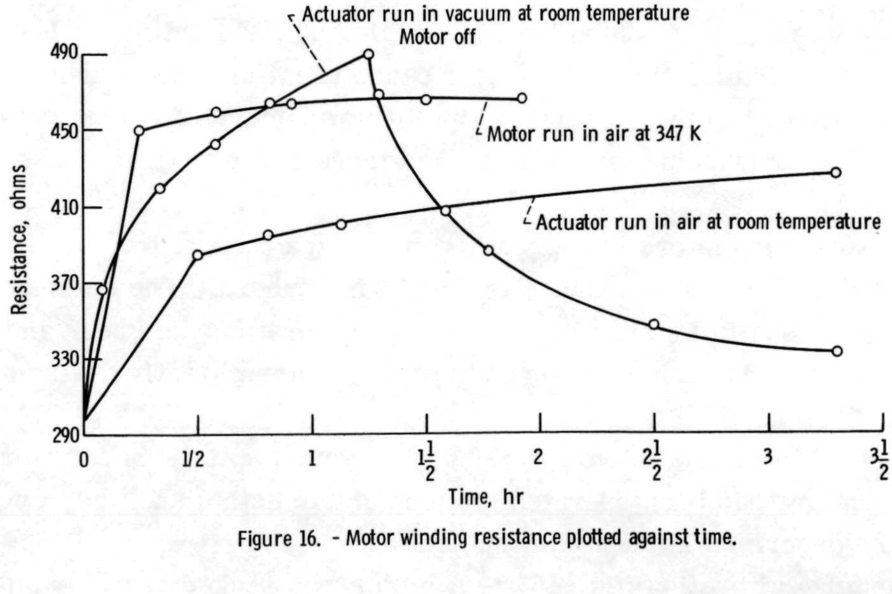


Figure 16. - Motor winding resistance plotted against time.

Winding resistance as a function of time at ambient (fig. 16). - An actuator was operated at ambient for 198 minutes. This test was performed to determine if the continuous running in alining the thruster system exceeded the temperature limits of the motor. This curve indicates that the actuators can withstand continuous running in air without damage.

Resistance as a function of time in vacuum at room temperature (fig. 16). - The same actuator was operated in vacuum for 75 minutes. The motor was shut off and the test was continued to determine the cooldown rate. After 50 minutes of continuous operation in vacuum, the motor winding resistance crossed the motor graph run at 347° K.

The maximum temperature of 464 K exceeded the maximum desired temperature of the windings. Using the maximum recommended temperature of the manufacturer and applying linear extrapolation, the operating time in vacuum should not exceed 60 minutes of continuous operation.

A practical duty cycle in orbit should be limited to 10 minutes on and 80 minutes off. On the basis of these tests it is questionable whether an actuator would operate more than 60 minutes without problems. However, an actuator had operated continuously for 7 hours and then an additional 4 hours in vacuum before failure. This long duty cycle occurred due to a wrong command sent during the prototype spacecraft vacuum testing.

REFERENCE

1. Renz, David D.; Zavesky, Ralph J.; Hurst, Evert B.: Evaluation of Failure Modes and Redesign of SERT II Gimbal Pin Puller. NASA TM X-2128, 1970.

NASA-Langley, 1971 —— 32 E-6449

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